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Analysis of Nimbus 3 SIRS Radiance Data: Traveling Planetary-Scale Waves in the Stratospheric Temperature Field[1]

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ABSTRACT—Zonal harmonics of the radiances measured by the three central channels of the SIRS instrument on Nimbus 3, representing vertically averaged temperatures in the lower and middle stratosphere, were computed. The traveling components of the lowest zonal wave numbers were estimated by the quadrature-spectrum method of Deland for periods of 1–12 cycles/mo.

The westward-traveling planetary-scale waves in the equatorial regions, previously described by Fritz, are approximately in phase with, and appear to be forced by, the westward-traveling planetary waves of middle latitudes. The traveling planetary waves are eastward traveling in high southern latitudes in winter, in contrast to an average slow westward motion in high northern latitudes in winter. The vertical structure of the traveling planetary-scale waves is remarkably uniform for all latitudes, with the temperature waves in the lower stratosphere (channels 6 and 7) lagging behind those in the middle stratosphere (channel 8) by approximately 2 days.

1. INTRODUCTION

Planetary-scale temperature fluctuations in the stratosphere have been studied for some time, but such investigations have been handicapped by the sparsity of data. Balloonsondes do not regularly ascend far into the stratosphere, and the rocket soundings are irregular in space and time. The accuracy of stratospheric pressure and temperature measurements has also been relatively low compared to measurements at lower levels. The satellite infrared spectrometer (SIRS) measurements from Nimbus 3 and 4 are valuable in many respects, in particular because of their almost global coverage with a single instrument of nearly constant characteristics. There are important practical problems in inverting the spectral radiance to obtain estimates of temperature; but, for the analysis of large-scale horizontal and time variability of the atmosphere, the data from the satellite-borne instruments are especially valuable.

The SIRS instruments measure radiance in eight narrow wavelength bands in the center and on the short-wave side of the strong 15-μm band of CO_2. In this paper, we consider only the data from the three channels nearest the center of the band, referred to as channels 6, 7, and 8 (Goddard Space Flight Center 1969, Fritz 1970); the channel number increases as one approaches the center of the band. The radiance reaching the sensor in a narrow wavelength-range region is the integral of the blackbody (Planck) radiation from the CO_2 in the atmosphere (which is assumed to be well mixed with constant mixing ratio), the integration being with respect to the optical mass ($d\tau = \rho_A A_\nu d\nu$, where A_ν is the absorption coefficient and ρ_A is the density of CO_2). The radiation for a particular wavelength may be considered to be a weighted mean of blackbody radiation (corresponding to the temperature) from different levels in the atmosphere multiplied by a weighting function of height. The weighting functions for the eight channels of the SIRS instrument for a standard atmosphere in which CO_2 is uniformly mixed (constant mixing ratio) are shown in figure 1. Channel 8, for the "most opaque" wavelength, receives radiation that is approximately proportional to the temperature of the emitting CO_2, mostly from the top 10 percent of the atmosphere. Maximum contribution comes from levels near 30 mb. The maximum contribution to channel 7 is from about 60 mb, the maximum for channel 6 is near 100 mb, and so on. Channel 8 receives relatively little from below 100 mb, (although some contribution down to 200 mb may be significant) especially when high clouds, which correspond to a large increment of optical depth at relatively low temperature, are present. Channel 7 receives larger contributions from below 100 mb, and channel 6 receives a relatively large contribution from the atmosphere near the tropopause at 200–300 mb. More details of the measurements are provided by Fritz (1970), who has already analyzed some aspects of these data.

There have been many studies of the large-scale temperature fluctuations in the stratosphere in addition to the work of Fritz just mentioned. Traveling planetary-scale waves in the stratospheric pressure field described by Boville (1967), Deland and Johnson (1968), Hirota (1968), Muench (1968), and others are associated with moving waves in the mean temperature of stratospheric layers. Some aspects of these waves, especially in low latitudes, have been described by Fritz (1970), who analyzed Nimbus 3 channel 8 data for 1969.

In this paper, we summarize the results of spectral analysis of the traveling waves using a method discussed by Deland (1972*a*). We describe their vertical and latitudi-

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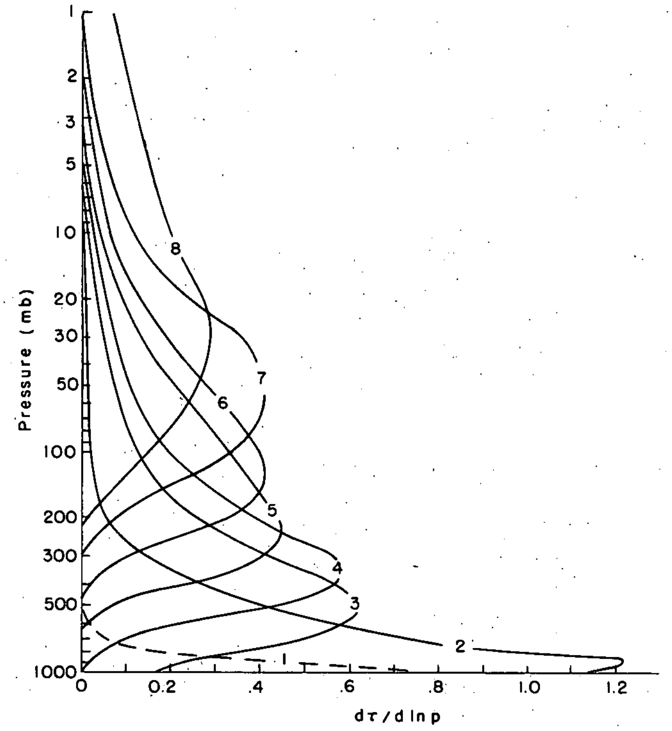

FIGURE 1.—Weighting functions for the eight channels of the SIRS A instrument on Nimbus 3.

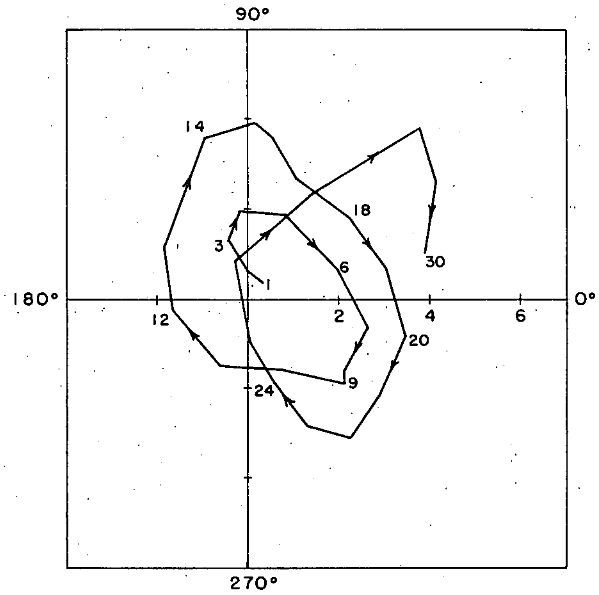

FIGURE 2.—Day-to-day variation of amplitude (10^{-7} J) and phase of zonal wave number 1 for channel 8 at 40°S during June 1969.

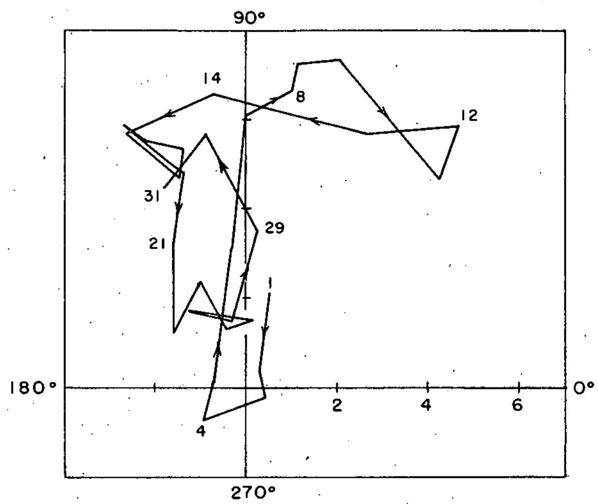

FIGURE 3.—Same as figure 2 for 60°S during July 1969.

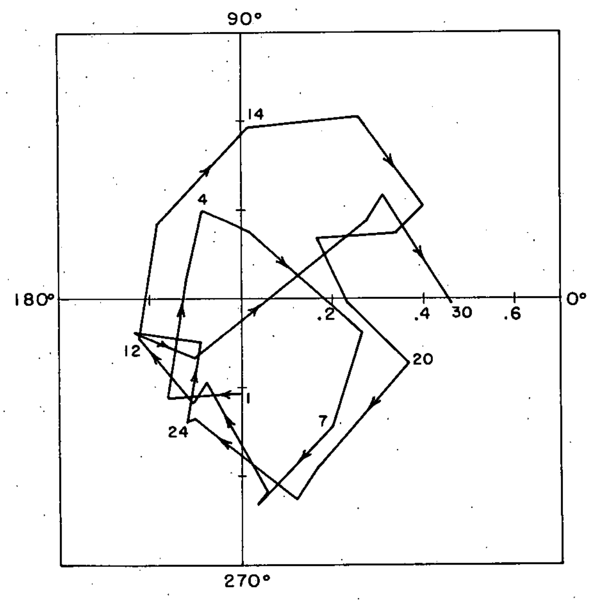

FIGURE 4.—Same as figure 2 at the Equator.

nal structure, comparing different channels and latitudes. We also compare the results with similar spectral analyses of the geopotential fields where these are available; that is, in the Northern Hemisphere. It is not practical to present in a journal article the detailed results, even to an extent sufficient to justify the main conclusions. We therefore describe the method of analysis, summarize the main results and conclusions in this paper, and refer interested readers to a more comprehensive report (Deland 1972*b*).

2. ANALYSIS

Zonal Fourier Analysis

The data for all orbits for 1 day were averaged over approximately 5° latitude bands from 85°S to 85°N, each averaged value being assigned to the longitude of crossing of the latitude circle by the satellite. Since our main interest was in the behavior of the planetary-scale waves, we linearly interpolated between the orbits to regularly spaced points 5° apart along the latitude circle and computed zonal Fourier harmonics (up to wave number 6) every 10° of latitude from 80°S to 80°N. These computations were done for each day during the period Apr. 14–Oct. 28, 1969.

Some results of the above analysis are plotted on harmonic dials in figures 2–4. In the figures, the amplitude and phase for a given day (for a given channel at a given latitude) are represented as a point on a polar diagram with amplitude plotted as radius and the longitudinal phase plotted as azimuth. The amplitude is plotted in $10^{-7}\text{J}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}\cdot\text{s}^{-1}$, which is approximately numerically equal to the amplitude of the corresponding harmonic of the weighted mean temperature in °C for the appropriate layer, according to figure 1.

The general clockwise motion of the points with time is apparent for low wave numbers in middle southern latitudes (fig. 2) and over the tropical regions (fig. 4). This clockwise motion represents decreasing longitudinal phase of the deviation from the mean and, therefore, westward motion of the corresponding wave. Due to the smaller amplitude of the mean planetary waves in the Southern Hemisphere, the westward-traveling waves in middle latitudes of the Southern Hemisphere are often of sufficient amplitude for the phase of the total wave (mean plus deviation) to change continuously through 2π; that is, the wave moves completely around the earth (see fig. 2) instead of oscillating about a mean position, as it usually does in the Northern Hemisphere. The amplitude of the variations in middle Southern Hemisphere latitudes in winter for wave number 1 (fig. 2) is typically in the range of $1–2\times10^{-7}$ J. This corresponds to a temperature wave of approximately the same numerical magnitude in degrees Celsius and, thus, agrees approximately with the average amplitude of the westward-traveling temperature wave in the lower stratosphere in winter deduced by Deland and Johnson (1968) from analysis of conventional data for the Northern Hemisphere. Wave number 1 shows similar westward motion in equatorial regions (fig. 4). Comparison of figures 2 and 4 indicates that the fluctuations at the Equator are, at times, approximately in phase with those at higher latitudes. The amplitudes of the traveling planetary waves in the Northern (summer) Hemisphere are small, only a few tenths of a degree, which is probably why they were not noticed in the conventional data by Deland and Johnson (1968).

It is of particular interest that the westward-traveling planetary waves are so well-defined in the Southern Hemisphere, where the quasi-stationary waves are much less developed than in the Northern Hemisphere, especially because of the negative correlation between the fluctuations of amplitude of the planetary waves and the zonal wind in the Northern Hemisphere. This circumstance indicates the existence of significant dynamical interactions of the traveling and stationary waves with the zonal wind in that hemisphere (Hirota 1968).

Traveling Wave Spectral Analysis

Figures 2–4 indicate that, over a large part of the globe during the period analyzed, most of the variability associated with the ultralong waves (viz, wave numbers 1 and 2) is due to the presence of traveling waves. This type of behavior has been described for the tropical regions by Fritz (1970), who analyzed the same data.

We have analyzed the time variations of the zonal harmonics using the traveling wave spectral analysis procedure developed by Deland (1972*a*). This technique estimates the amplitude, direction of motion, and phase of the traveling wave at each of the frequencies that are harmonics of the fundamental frequency corresponding to the period analyzed (i.e., $1/T$, $2/T$, $3/T$, . . ., $(N-1)/T$). Each frequency, ω, corresponds to a wave speed, ω/N_z where N_z is the zonal wave number. The analysis is the discrete Fourier series equivalent of the quadrature spectral analysis procedure used by Deland (1964) and Eliasen and Machenhauer (1969). The principal advantage of discrete harmonic analysis over methods based on the Fourier transform of lag correlation functions is that phase information is more directly and reliably derived using discrete harmonic analysis. Much of this paper is concerned with the comparison of the phases of the waves at different levels and latitudes.

Latitudinal Structure of Ultralong Traveling Waves

In figures 5 and 6, the amplitudes (10^{-7} J·cm^{-2}·sr^{-1}·s^{-1}) of the traveling wave components from 1 to 10 cycles/mo for wave numbers 1 and 2, for channel 8 (the "highest" channel) are shown as functions of latitude for May, August, and October. The amplitudes, positive for eastward-traveling components and negative for westward, were plotted for each frequency at each latitude. To improve legibility without significant loss of information, we reproduced only maximum and minimum values (considering variation with latitude for a particular frequency) in the figures, so that variation between plotted amplitudes for each frequency is monotonic. Since the variation of Fourier harmonics with latitude can be presumed to be continuous, the line separating positive from negative amplitudes can be considered to be the zero isopleth of amplitude; therefore, minimum values adjacent (in latitude) to the zero line are not plotted. Amplitudes decrease montonically with latitude from the nearest plotted value to the zero line. Since a finite amplitude at either pole is impossible, the amplitude at the pole is taken to be zero. The highest latitude amplitude plotted is, therefore, a maximum with monotonic decrease for increasing latitude. The zero line was drawn to separate positive and negative amplitudes as calculated with no smoothing.

Even though figures 5 and 6 present amplitude only and random fluctuations are apparent, some important aspects of the behavior of the traveling waves are clearly shown. For wave number 1, westward-traveling components, from 1 to about 9 cycles/mo (speeds of 12°–108° longitude/day), generally prevail from middle northern to middle southern latitudes. In northern latitudes north of about 50°N, neither eastward- nor westward-traveling components predominate; but, in high southern latitudes, eastward-traveling components are generally found. For each of the wave numbers considered (and for shorter waves, also), the greatest amplitudes of the traveling waves occur in middle and higher latitudes of the Southern Hemisphere, which is the winter hemisphere for the period analyzed. The amplitudes of the largest amplitude traveling wave components in the Southern Hemisphere,

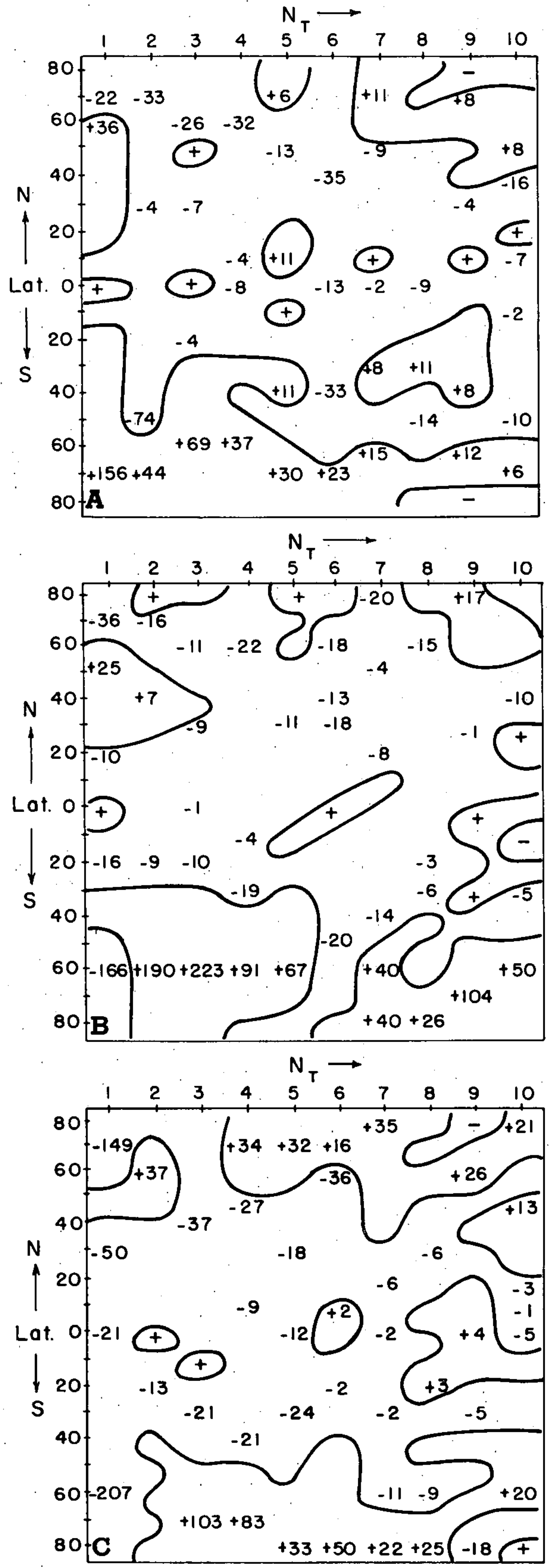

FIGURE 5.—Amplitudes of traveling components, zonal wave number 1, channel 8, plotted against frequency in cycles/mo and latitude for (A) May, (B) August, and (C) October. Values plotted (10^{-9} J) are relative maxima and minima; positive amplitudes for eastward motion, negative for westward.

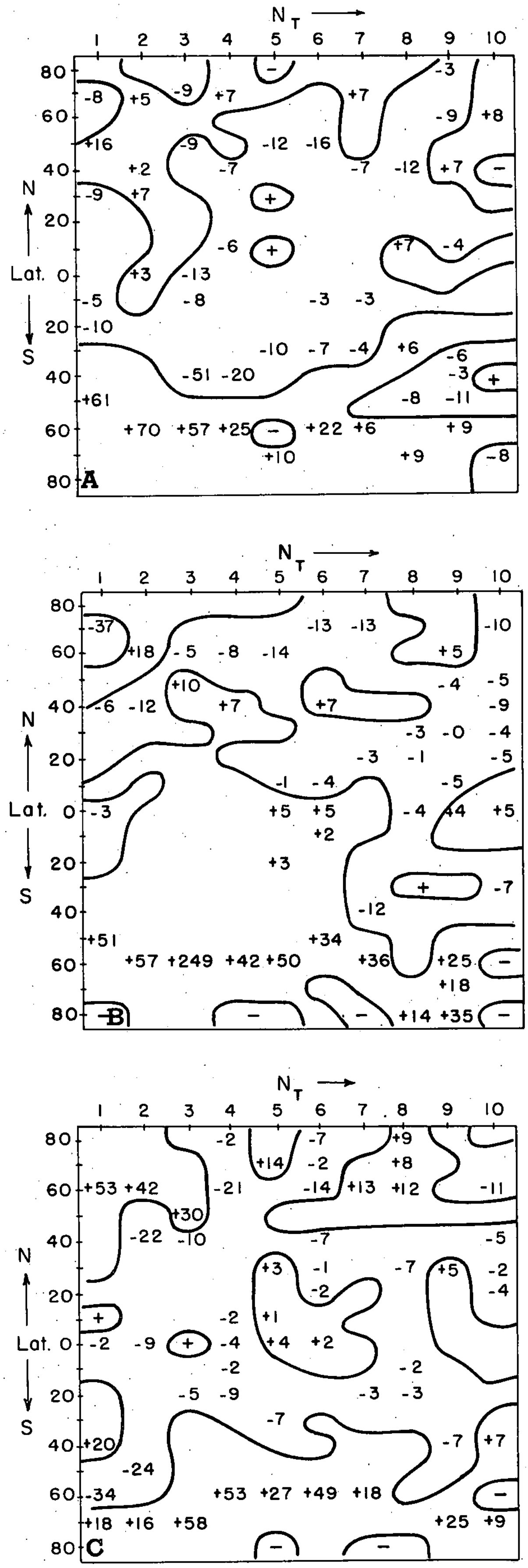

FIGURE 6.—Same as figure 5 for wave number 2.

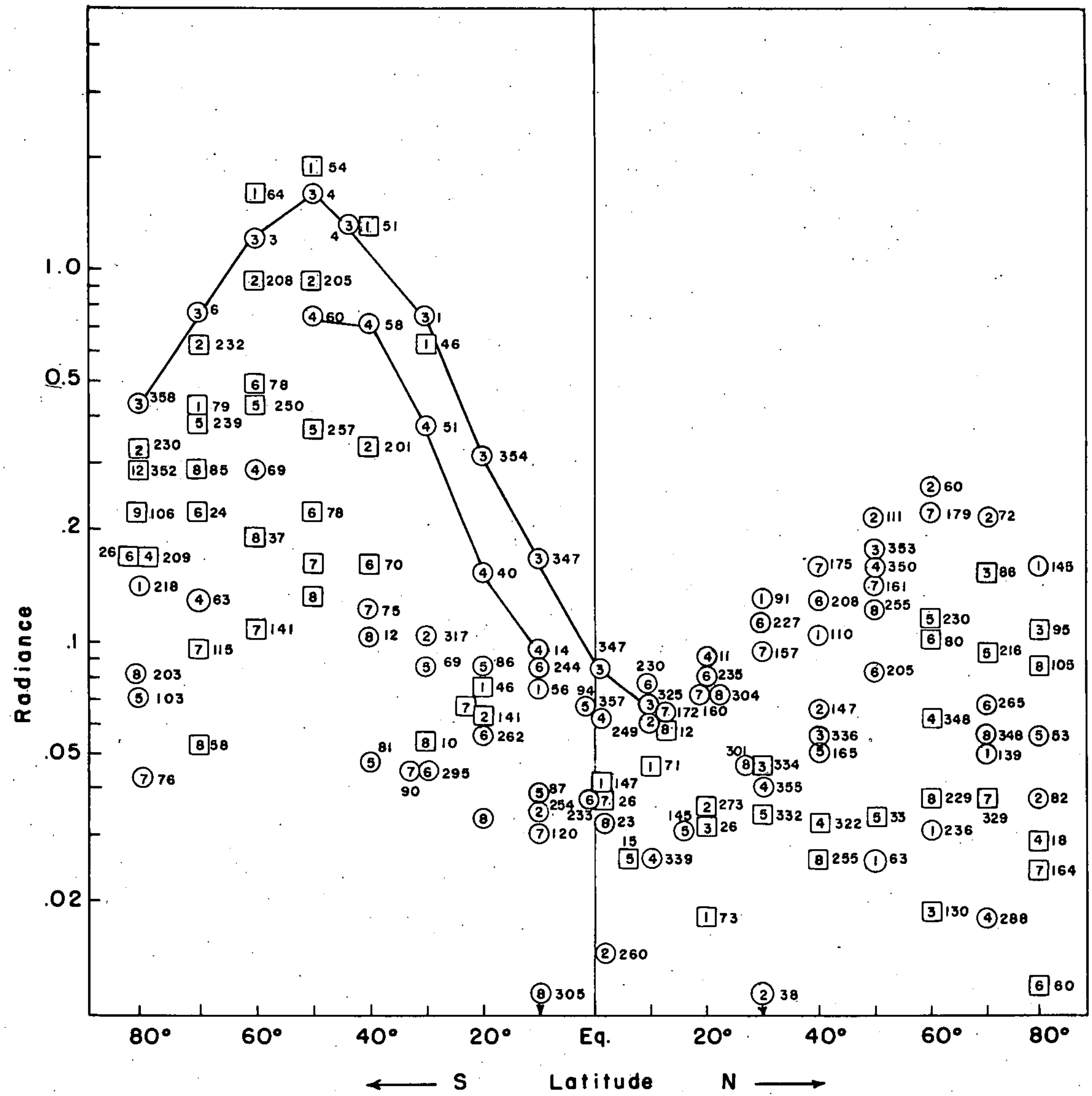

FIGURE 7.—Amplitude of principal traveling components, for channel 8 zonal wave number 1 at each latitude in July 1969. Ordinate is amplitude in 10^{-7} J · cm^{-2} · sr^{-1} · s^{-1}. Frequency in cycles per month is written in a circle for westward motion, a square for eastward motion, with phase written along side. For points connected by lines, phases differ by less than 90° from the equatorial value.

at about 60°S, are of the order of 10^{-7} J, which corresponds to a total amplitude of roughly 2×10^{-7} J. This is consistent with figures 2 and 3. Because of the continuity of amplitude and direction of movement, the equatorial traveling waves appear to be extensions of those in higher latitudes.

The spectra for zonal wave number 2 for the same months are shown in figure 6. In general, wave number 2 shows more eastward motion than wave number 1. The high (southern) latitude eastward motions appear to extend to lower latitudes than in the case of wave number 1 and, in August in particular, are continuous with eastward motion in the equatorial region, monotonically decreasing in amplitude with decreasing latitude. There is mainly eastward motion in some months and westward in others in the equatorial region. The wave motions at the Equator appear to be extensions of those in middle latitudes in the case of wave number 2 as well as wave number 1. We have examined the traveling wave spectra for wave numbers 3 and 4, also. For these wave numbers, there is a similar general pattern of eastward motion at high and middle southern latitudes and westward motion elsewhere. The pattern becomes less coherent with increasing wave number. In most months, the equatorial harmonics, which are of very small amplitude on the average for harmonics 3 and 4, appear random. They show little evidence of a connection with higher latitudes.

If the waves at different latitudes are physically related, the phases of the computed waves should be similar or vary systematically. The amplitude and phases are shown in figure 7 for the harmonics of the largest amplitude, according to latitude, for channel 8 for zonal wave number 1 of July. The amplitude of each frequency (corresponding to wave speed) is plotted against latitude. The point representing the amplitude is plotted as a circle or square according to whether the computed wave speed is westward or eastward, respectively, with the frequency in cycles per month written inside. The phase in degrees is written adjacent to the circle or square. The phase represents longitudinal position of, for instance, the maximum (ridge in conventional synoptic meteorological terminology) at any fixed time. For the westward-traveling components, the phase gives the longitudinal position at the beginning of the month directly; for the eastward-traveling components, the longitudinal position at the beginning of the month is given by the timewise phase subtracted from 2π.

As illustrated in figure 7, the largest amplitude harmonics of zonal wave number 1 are remarkably continuous in phase as well as amplitude (as long as the direction of motion remains the same) over wide ranges of latitude. In many cases, the phases deviate by less than 90° from the Equator to latitude 50° to 60° north or south. Amplitudes also vary systematically with latitude for particular frequencies. The latitudinal structure does not appear to be dependent on frequency; for the principal harmonics, the amplitude at the Equator is a roughly constant (with respect to frequency) fraction of that in middle latitudes, and the phases are approximately equal.

Inspection of the phases of the principal harmonics plotted in figure 7 indicates that they tend to increase (shift eastward) with increasing latitude for westward-traveling components; the eastward-traveling components are few and their phases are erratic. For all 6 mo, most of the principal harmonics of zonal wave number 1 at the Equator have phases shifted westward with respect to the phases of the large-amplitude traveling waves in middle latitudes, especially in southern latitudes where the amplitudes are largest.

Wave number 2 was analyzed in the same way as wave number 1. The principal westward-traveling components at the Equator agreed well in amplitude and phase with the corresponding components at 30°N and 30°S, when these components were traveling in the same direction. Perhaps because of greater scatter, no systematic shift of phase with latitude was apparent. Wave numbers 3 and 4 were analyzed in the same way and showed little evidence of consistency of motion at the Equator; they appear to be essentially random.

Vertical Structure of Traveling Planetary-Scale Waves

As is apparent from the behavior of the traveling planetary-scale waves (TPSW) with latitude, the waves appear to fall into three of four categories, for which vertical structure can be considered separately for convenience. For each of these categories, the spectral results for different channels will be compared to determine the vertical structure of the waves as far as possible using this method of analysis.

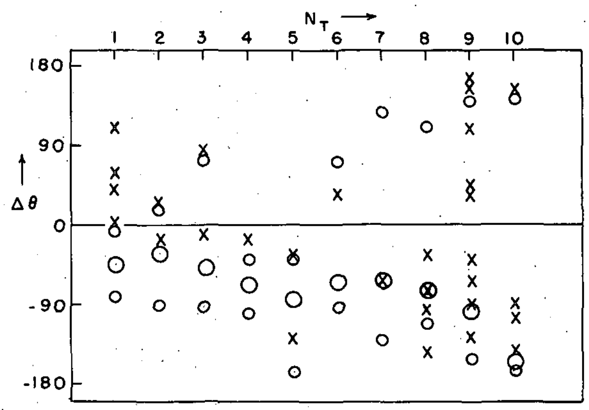

FIGURE 8.—Phase difference, $\Delta\theta$ (channel 8 vs. channel 6), plotted as a function of frequency for traveling components of zonal wave number 1 for April, September, and October at 30°N, 40°N, 30°S, and 50°S. Median and extremes are plotted for westward propagation (circles); all cases are plotted for eastward propagation (crosses).

Westward-traveling planetary-scale waves in middle latitudes. These appear to be best defined and of largest amplitude at about 40°N or 30°S in the equinoctial months (figs., 5, 6). The amplitude of the waves is often larger at 50° or 60°S, but the computed amplitudes are more variable than at lower latitudes, where the motion is more consistent.

The amplitudes of the westward-traveling waves of wave number 1 increase with increasing channel number in the approximately equinoctial months; the amplitudes for channel 8 are two or three times as large as those of channel 6. For wave number 2, the amplitudes of channels 7 and 8 are about the same and are larger than for channel 6, indicating a leveling-off of the increase of the temperature wave with height.

The variation of phase with height is shown in figure 8 for wave number 1. For each frequency from 1 to 10 cycles/mo, the differences in phase for channel 8 versus channel 6 are plotted for April, September, and October for latitudes 30° and 40°, both north and south. Phase differences are meaningful only if phase velocities are of the same sign, so not all possible differences are included. Both westward- and eastward-traveling components are plotted, the first as circles and the second as crosses. For the westward-traveling components, only median values and extremes are plotted. Since eastward-traveling components are relatively few in number, all of them are plotted. From channel 6 to channel 8, the westward-traveling waves are displaced westward, indicating westward tilt of the temperature wave. Except for the components of frequency 1 cycle/mo and for higher frequencies for which amplitudes are small and phases erratic, the phase shift for the westward-traveling components increases approximately in proportion to frequency, corresponding to a constant time difference with channel 8 leading channel 6 by about 2 days.

Eastward-traveling planetary-scale waves in higher southern latitudes. The amplitudes for wave number 1 increase upward, channel 8 amplitudes being about twice as large as those for channel 6. For wave number 2, the amplitudes

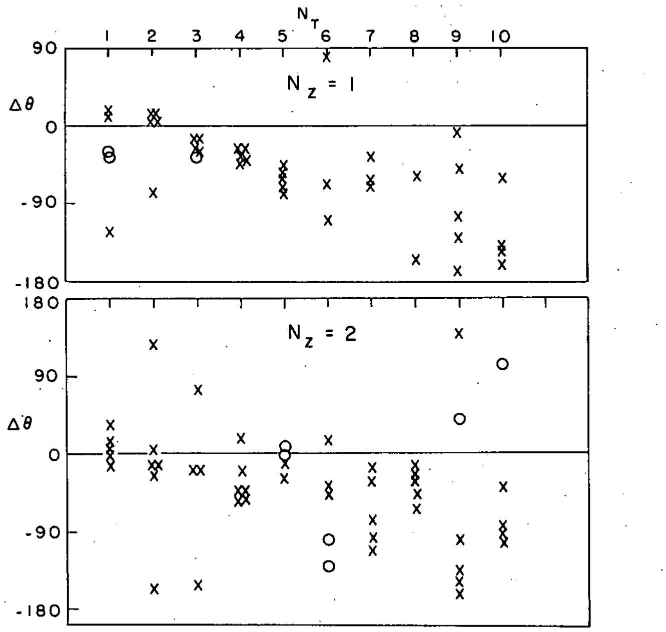

FIGURE 9.—Phase difference, $\Delta\theta$ (channel 8 vs. channel 6), plotted as a function of frequency for traveling components of zonal wave numbers 1 and 2 for July, August, and September at 60° and 70°S. All values are plotted; circles for westward propagation, crosses for eastward propagation.

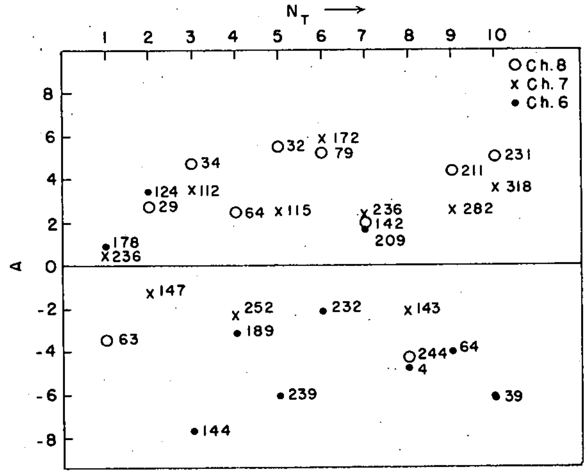

FIGURE 10.—Amplitude (10^{-9} J) and phase of traveling components of zonal wave number 2 at the Equator in August, for all three channels.

for channel 7 are, on the average, greater than for the other two channels, indicating that the temperature wave increases in amplitude up to low or middle stratospheric levels (roughly 30 mb) and decreases above, in contrast to the behavior of the westward-moving wave number 1 described previously.

The phase differences from channel 6 to channel 8 are plotted in figure 9. The phase decreases with increasing height on the average (the difference increasing with frequency), corresponding again to an approximately constant time shift of about 2 days from channel 6 to channel 8, with the higher channel 8 leading the lower channel 6. For these eastward-traveling components, the phase shift corresponds to an eastward phase shift with increasing height—an unexpected result. Because of the approximately constant time difference at lower frequency (corresponding to decreasing longitudinal "tilt" with decreasing frequency), the eastward- and westward-traveling components are consistent with no discontinuity at zero phase speed; stationary fluctuations would presumably be vertical.

It is difficult to define a relevant mean zonal flow for these waves that extend through a large fraction of the atmosphere, including the troposphere. The eastward-traveling waves at higher frequencies appear, however, to be stationary or even eastward moving relative to the mean flow. The eastward longitudinal speed for wave number 1 at 45°S is 33 m/s for 3 cycles/mo and 77 m/s for 7 cycles/mo. Although we have relatively few cases of eastward-traveling components in the Northern Hemisphere (figs. 5, 6), those that occur also tilt eastward.

Equatorial traveling waves. The amplitudes and phases for channel 6 are erratic in the equatorial region, presumably because of small amplitudes and interference from high clouds.

Like those at ±40° discussed previously, the amplitudes of equatorial traveling waves increase upward from channel 7 to channel 8 by a factor of about 1½. The phases shift westward with increasing height for the westward-traveling components; the eastward-traveling components are few with small amplitudes, and their phase shifts are too variable for any conclusions about average behavior to be drawn. The phase shifts for the westward-traveling components are approximately proportional to frequency for the relatively large amplitudes at low frequencies, again corresponding to an approximately constant time shift, with channel 8 leading channel 7 by about 2 days. The structure of the waves again appears similar to that of the much larger amplitude waves of higher latitudes. The vertical structure of these waves in the equatorial region is remarkably constant from month to month.

During August, wave number 2 moves eastward at the Equator. The spectra for the three channels for this case are shown in figure 10 with amplitudes and phases plotted on the same diagram. Each harmonic is plotted with amplitude as ordinate, positive for eastward and negative for westward traveling components; and the phase of the harmonic is written alongside the plotted point. The harmonic is plotted as a dot, cross, or circle for channel 6, 7, or 8, respectively. The largest amplitude eastward-traveling components in this case increase (in amplitude) from channel 7 to channel 8, and the (timewise) phases again decrease with increasing channel number, corresponding to the eastward phase shift with increasing height of the corresponding eastward-traveling components in southern latitudes (fig. 9). Whether the phase shift corresponds to an approximately constant time difference as in middle latitudes (figs. 8, 9) is an open question because of the small sample.

Westward-traveling temperature waves in the summer stratosphere. These waves appear, on the average, to be constant with height with westward phase shifts, corresponding to channel 8 leading channels 6 and 7 by approximately 2 days. The spectra for the 30-mb height in the Northern Hemisphere for the same months and latitudes were also analyzed and compared with the SIRS data. The 30-mb components are consistent in that most of the larger amplitude westward-moving harmonics at 30 mb are paired with westward-displaced, westward-moving harmonics in the SIRS data. The phase displacements from 30 mb to channel 8 are particularly large, between 90° and 180°. The radiance (temperature) waves are of relatively small amplitude (on the order of 10^{-8} J or a few tenths of a degree) and are strongly rotated so as to be almost out of phase with respect to the geopotential harmonics.

Interhemispheric Comparison

Previous evidence of systematic eastward motion of planetary-scale waves in high southern latitudes is sketchy (Phillpot 1964). Van Loon and Jenne (1972) are skeptical, but their own data (see their fig. 14) indicate average eastward motion of the transient wave number 1 at 500 mb near 60°S. The observations discussed in this paper appear to contrast with those of Deland and Johnson (1968), Deland and Friedman (1972), Hirota and Sato (1969), and others, for the Northern Hemisphere, for which westward-traveling ultralong waves appear to prevail in winter as well as in summer.

The apparent difference between the middle latitudes of the two hemispheres in winter is of considerable interest, for it appears to be greater than can be explained simply by the greater average zonal wind in the Southern Hemisphere winter than in the Northern Hemisphere winter: a difference of approximately 10 m/s corresponds to a frequency of only 1 or 2 cycles/mo for wave number 1 at latitude 60°. The difference may be related to the observation that the summer–winter difference of average wave speed in the Northern Hemisphere (Deland and Johnson 1968) also appears to be larger than can be accounted for simply by the summer–winter difference of vertically averaged zonal speed. More definite observational evidence on this question should be forthcoming when more of the satellite data (for at least a whole year) are analyzed.

Comparison of the two hemispheres in approximately corresponding seasons can be made using the SIRS data alone. We have almost exactly 6 mo of data; therefore, although we cannot compare results from the two hemispheres 6 mo apart, "April" (April 14–May 13) and October can be considered, with caution, as representative of equinoctial conditions for both hemispheres even allowing for seasonal lag. If one considers the first four zonal harmonics together, asymmetry of motion in the two hemispheres appears well established, at least for these months. Although the equinoctial data are slightly biased toward the Southern Hemisphere winter–Northern Hemisphere summer period, the variation from 1 mo to the next is not large, and the difference appears to be real for this period. The sample is small, of course, and the above observation must be considered suggestive rather than definitive.

3. CONCLUDING REMARKS

The coherence of the ultralong traveling waves at middle and equatorial latitudes and the eastward average phase shift with increasing latitude (at least for wavenumber 1) are strong evidence that the equatorial waves described by Fritz (1970) are forced by the westward-traveling planetary-scale waves in middle latitudes. The westward tilt with increasing height of the westward-traveling waves in middle latitudes indicates that the stratospheric traveling waves are forced from below. The apparent lateral forcing of the equatorial waves by middle latitude disturbances does not preclude upward forcing as well, for the same traveling planetary-scale waves may extend into equatorial latitudes at lower levels even though theoretical studies (Dickinson 1971) have indicated that this is unlikely. Slantwise propagation, as has been discussed by Matsuno (1971) in relation to the stratospheric warming phenomenon, is also possible.

The propagation of middle latutide disturbances into the Tropics has been studied theoretically by several other authors, including Mak (1969), Dickinson (1971), and Manabe et al. (1970). In a numerical integration of a global atmospheric model, Manabe et al. (1970) found westward-propagating ultralong waves in the "upper troposphere" or "stratosphere," according to the vertical resolution of the model, for which energy was derived primarily from latent heat of condensation rather than interactions with higher latitudes. Comparison of the observations of this paper with results of numerical integrations would require more detailed analysis of the vertical structure of the model results than has so far been presented. The eastward tilt of the eastward-traveling components appears to correspond to downward propagation of energy in the case of the slower moving components. If we may apply the Eliassen and Palm (1961) theory "locally," in the stratosphere in high southern latitudes in winter, the results indicate that the traveling planetary-scale waves transfer energy downward in this region, which requires compensating energy conversions by mean meridional motions (Dickinson 1969). The eastward-traveling planetary-scale waves could be forcing mean upward motions; that is, an indirect circulation opposite to that deduced for the corresponding region of the Northern Hemisphere. The contribution of the slow, eastward-moving, planetary-scale waves may be overshadowed by that of other components but could be responsible for significant differences in the mean meridional circulations of the two hemispheres.

In addition to being part of the upper boundary conditions for existing or presently feasible numerical models of the atmosphere used for general circulation studies and forecasting purposes, the propagation of planetary-scale fluctuations through the stratosphere and mesosphere into the ionosphere makes an important contribution to the variability of the ionosphere. The westward tilt of the traveling waves with increasing height does not appear to be consistent with the close agreement (apparently within 2 days in time and less than 30° of longitude) of fluctuations in the ionosphere with planetary-scale fluctuations in the stratosphere (Kawahira 1970, Deland and Friedman 1972, Deland and Cavalieri 1973). Whether the close matching of ionospheric and stratospheric variations is due to filtering out of the more strongly tilted, faster moving waves with increasing height, to filtering out of the traveling waves in general, leaving approximately vertical and simultaneous stationary fluctuations, or to other reasons can only be decided by analysis of observations of the mesosphere. The selective chopper radiometer data from the Nimbus 4 satellite or the data that are expected from the limb-scanning radiometers planned for later satellites should serve this purpose.

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